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THERMO-MECHANICAL COMPATIBILITY OF CFRP VERSUS STEEL REINFORCEMENT FOR CONCRETE AT HIGH TEMPERATURE

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ABSTRACT: Sustainability considerations in the design of concrete structures have become a driver for the use of non-conventional reinforcing materials. One example of this is the emerging use of non-corrosive, high-strength, and lightweight carbon fibre reinforced polymer (CFRP) prestressing tendons. It is widely known that the bond between FRP reinforcing tendons and concrete deteriorates at elevated temperature due to a combination of factors. Lateral thermal expansion of FRP reinforcing tendons at elevated temperature has been shown to have consequences for the bond performance of these systems. This paper presents the results of an experimental study carried out to assess the occurrence of heat-induced longitudinal splitting cracks in concrete specimens reinforced with CFRP or steel prestressing tendons. A novel testing methodology, namely a Heat-Transfer Rate Inducing System (H-TRIS), is used to subject specimens to thermal loading which replicates that experienced by equivalent specimens in a standard fire resistance test. A comparison between CFRP and steel tendons is made, and the occurrence of longitudinal splitting cracks is evaluated in terms of the time to occurrence and thermal gradient within the concrete. Results are compared against an available analytical model.

1. Introduction

The use of FRP tendons to replace traditional steel reinforcement is motivated predominantly by a desire to prevent electrochemical corrosion of the internal reinforcement, and thus to enable design of more slender and durable structural elements. However, this raises two noteworthy concerns with regard to fire safety design considerations:

1. Because there are essentially no concerns regarding electrochemical corrosion of the FRP tendons, the concrete cover can be considerably less than in steel-reinforced or prestressed elements (Bafalas and Burgoyne 2012). This allows the design of slender elements without the increased risk of corrosion, but with an increased risk of failure due to more rapid temperature increase of the reinforcement in case of fire. Most fire safety design guidelines for steel reinforced concrete structures consider the temperature of the reinforcement, which depends fundamentally on the concrete cover depth, to be a fundamental design criterion for the fire safe design of reinforced and prestressed concrete (CEN 2004).
2. Reductions in bond strength between steel reinforcement and concrete are not generally considered to be a governing factor dictating the fire resistance of steel reinforced or prestressed concrete elements (Katz and Berman 2000). It has been shown, however, that bond strength degradation between FRP tendons and concrete at elevated temperature may be considerably more critical than loss of the tendon's tensile strength (Bisby et al. 2005). Thus, bond strength capacity appears to be a limiting factor for the fire safety design of FRP reinforced and/or prestressed concrete; although the magnitude of bond strength reductions and their impacts on the load-bearing capacity of heated FRP reinforced or prestressed concrete structures remain largely unknown or have not been demonstrated (Bisby et al. 2005).

Prior research aimed at better understanding the performance of FRP reinforced or prestressed concrete elements in fire (e.g. Bisby et al. 2005) have shown that loss of bond strength of FRP reinforced or prestressed concrete structural elements are frequently driven by thermo-mechanical bond degradation and/or the appearance of longitudinal splitting cracks during heating.

Because it is likely that thermo-mechanical bond degradation between FRP tendons and concrete at elevated temperature is more critical than loss of the FRPs' tensile strength (Bisby et al. 2005), FRP tendons' bond strength reductions are considered the limiting factor for the fire-safety of FRP reinforced and prestressed concrete (Katz et al. 1999). The bond strength of FRP tendons relies primarily on the strength and stiffness of the polymer resin matrix at the bars' surface, which typically incorporates a sand coating, spiral fibre rovings, and/or a ribbed shaped resin surface. The glass transition temperature (T_g) of an FRP's polymer resin is widely used to define the limiting temperature at which degradation of the tensile (and bond) strength of composite materials occurs (CNR 2006, ACI 2007), yet the research to support such an approach is scarce. A prior comprehensive experimental study on thermo-mechanical bond degradation of CFRP tendons has been presented by the authors (Maluk et al. 2011).

FRP tendons exhibit considerably different coefficients of thermal expansion (CTE) in the longitudinal and transversal directions, and these differ substantially from concrete. In the longitudinal direction FRPs have lower (even negative) CTEs. In the transverse direction, FRPs' CTEs are governed mostly by the polymer resin matrix and the fibre volume fraction, and are typically much (i.e. an order of magnitude) larger. For the CFRP tendons used in the current study, the CTEs in the longitudinal and transverse directions were measured in the range of 2×10^{-7} /°C and 3.6×10^{-5} /°C, respectively, while the CTE of concrete (and steel reinforcement) is typically around 1×10^{-5} /°C (CEN 2004). Some (mostly theoretical) studies have been carried out previously to try to understand the effects of the differential thermal expansion between FRP bars/tendons and surrounding concrete, since this is thought to contribute to generation of longitudinal splitting cracks and eventual failure of the concrete cover's ability to provide sufficient confining action for tensile bond development and force transfer (Aiello et al. 2001, Abdalla 2006).

2. Aims of the Study

Results from an earlier set of standard fire resistance tests performed between 2009 and 2010 showed that the failure mode of precast CFRP pretensioned high-performance self-consolidating concrete (HPSCC) slabs was highly influenced by accumulated heat-induced concrete cover spalling (Terrasi et al., 2012). For the few slabs in these prior tests for which no cover spalling occurred during fire testing, early failure (about 30 minutes from the start of the test) was driven by loss of bond between the CFRP and the concrete in the prestress transfer zones; this was though to be induced by the appearance of heat-induced longitudinal splitting cracks in combination with thermo-mechanical degradation of bond strength due to softening of the tendons' epoxy-bonded sand coating (Terrasi et al., 2012).

The current study aimed to experimentally assess the occurrence of heat-induced longitudinal splitting cracks on concrete specimens reinforced with steel or CFRP reinforcing tendons. A novel testing methodology was developed, called the Heat-Transfer Rate Inducing System (H-TRIS), and was used to subject steel and CFRP reinforced HPSCC test specimens to a quantifiable thermal loading which was defined so as to replicate heating experienced by equivalent specimens in a fire testing furnace. A comparison was made between HPSCC specimens reinforced with steel and CFRP bars and the occurrence of longitudinal splitting cracks is evaluated in terms of time-to-occurrence and thermal gradient within the concrete. The concrete mix used in this study was designed with the inclusion of polypropylene microfibres in order to assure no occurrence of heat-induced concrete cover spalling during testing, as was concluded from a previous study by the authors (Maluk et al. 2013) (see Table 1).

Table 1 – Concrete mix compositions and slump flow measurements.

Water/ (cement + microsilica + fly ash)	Cement (20% microsilica)	Fly ash	Limestone aggregate (0-8 mm)	Super-plasticizer	Dose of PP fibres	Slump flow (CEN, 2010)
[-]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[% cement]	[kg/m3]	[mm]
0.31	474.5	120.0	1675.2	1.69 %	2.0	830

3. Test Setup and Experimental Program

The H-TRIS test methodology uses a mobile array of propane-fired radiant panels with a mechanical linear motion system, as shown in Figure 1, in an effort to simulate the time-history of heat flux experienced by a tested specimen in a standard fire resistance test (CEN 2012); this is based on through thickness temperature measurements recorded during furnace testing where the furnace temperature is controlled by measuring the internal gas temperatures (Maluk et al. 2012). Thermal loading of specimens is controlled in H-TRIS using imposed incident heat flux that are calibrated using measurements from a water-cooled Schmidt-Boelter heat flux sensor during a pre-programmed calibration run. Calibration is be repeated before each new test to account for the specific ambient conditions on any given day. Essentially, a computer-controlled linear motion system is used to adjust the location of an array of high intensity radiant heating panels (i.e. their distance from the test specimen) allowing tests to follow any pre-defined time-history of incident heat flux. H-TRIS thus allows accurate quantification of the thermal energy absorbed by a tested element with good repeatability and at negligible economic and temporal costs compared to furnace tests (Maluk et al. 2012).

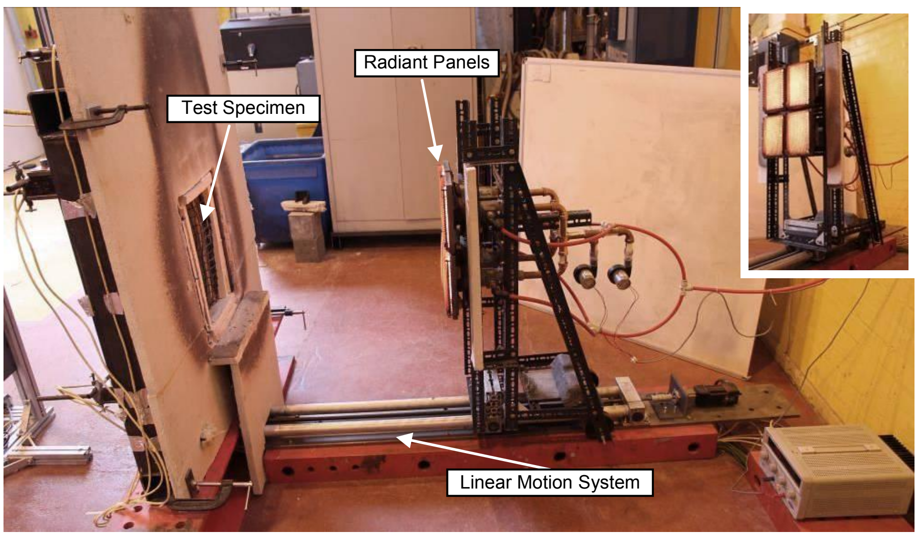

Fig. 1 – Current version of Heat-Transfer Rate Inducing System (H-TRIS) at Edinburgh.

For the current study H-TRIS was programmed to impose a thermal loading on the test specimens defined to be equivalent to the thermal loading experienced by full scale CFRP prestressed HPSCC slabs previously tested in furnace tests (see Terrasi et al. 2012). All test specimens had a transversal cross section of 45 mm × 200 mm, identical to the large-scale specimens. Tendons (CFRP or steel) were located at the slabs' mid-depth with a tolerance of ±2 mm. The lateral concrete cover at the slab edges was 22 mm, and the tendon-to-tendon clear spacing was 44 mm (Figure 2). It is noteworthy that in structural fire resistance tests scaling is important on various grounds (Harmathy and Lie 1970); this is why specimen cross-sectional dimensions were not scaled. Unheated of 50 mm were required at the ends to support the specimens during testing, giving a thermally exposed surface of 400 mm × 200 mm.

Fig. 2 – Cross section (45 mm × 200 mm) of a specimen reinforced with unstressed CFRP tendons.

Three specimens each of samples reinforced with unstressed CFRP or steel bars were tested under free-to-expand, unrestrained support conditions. After casting test specimens were kept under a polyethylene sheet for 2 days and then left to cure in a temperature (20°C) and humidity (80% RH) controlled environment until testing at an age of about 14 months. Pultruded, quartz sand-coated CFRP tendons made from Tenax UTS carbon fibres, at a fibre volume fraction of 0.64, and Bakelite 4434 epoxy resin were used for this study. The tendons' design tensile strength was 2000 MPa with a design elastic modulus of 150 GPa. The quartz sand coating had an average grain size of 0.5 mm and was bonded in-line after the pultrusion process using the same epoxy resin to promote bond strength. The diameter of the CFRP tendons was 5.4 mm and the total diameter, including the sand coating, was approximately 6.0 mm. The steel reinforcement was nominally 6.0 mm in diameter with a yield strength (at 0.2% offset strain) of 1592 MPa, an ultimate strength of 1749 MPa, and an initial elastic modulus of 210 GPa. The 0.2% offset yield strain was 0.76% and the ultimate strain was 5.4%.

4. Results and Analysis

During testing the exposed and unexposed surfaces of the specimens were monitored for the appearance of surface longitudinal splitting cracks. All three CFRP reinforced specimens displayed first longitudinal splitting cracks at the unexposed surface at about 12 minutes from the start of the test (refer to Table 2). Based on tests results from a previous study in which through-thickness temperature measurements were performed (Maluk et al. 2013), it is estimated that temperature at the lower edge of the CFRP tendon was about 160°C at this instant.

At the exposed surface no visible cracks were observed, however flames were observed from 27 minutes (or more) from the start of the test, at which temperature at the lower edge of the CFRP tendon was estimated to be at about 350°C. This is thought to be associated with decomposition of the CFRP's epoxy resin matrix at temperature as observed from thermogravimetric analysis (TGA) performed on identical CFRP tendons (Maluk et al. 2011). Tests were carried for a total duration of 60 minutes. Figure 3 shows the appearance of longitudinal splitting cracks at the unexposed surfaces of the CFRP reinforced specimens after cooling. All three steel reinforced specimens failed to exhibit any obvious surface longitudinal splitting cracks at either their exposed or unexposed surfaces during testing.

Table 2 – Test observations for specimens reinforced with CFRP tendons.

Test Specimen	First crack at the unexposed surface [mm:ss]	First flame at the exposed surface [mm:ss]
#1	12:03	27:50
#2	11:28	30:57
#3	11:41	31:48

A thermo-mechanical analytical model developed by Aiello et al. (2001) for modelling the formation of longitudinal cracks was employed for comparison with experimental test results observed during this study. Aiello et al.'s model assumes that:

- each FRP tendon is treated independently, meaning that the clear spacing between two adjacent tendons is sufficient to avoid the occurrence of horizontal splitting cracks at the tendon's level; this is a reasonably good assumption for the samples tested herein;
- the temperature at FRP tendon and concrete increases uniformly (i.e. there is no through-thickness thermal gradient within tested specimens, which is clearly not the case in the current tests); and
- the temperature dependent elastic modulus and tensile strength of concrete can be used as inputs.

A thorough description of the model, along with an applied formulation for the conditions encountered in the test setup described in this paper, has previously been presented by the authors (Maluk et al. 2010). Based on these results it was concluded that crack formation should indeed occur more rapidly at the unexposed surface in the presence of a thermal gradient and that there is a direct dependency between the crack formation and the concrete temperature (i.e. the through-thickness temperatures in concrete). Further modelling is needed before quantitative predictions can be made.

Fig. 3 – Unexposed surfaces of CFRP reinforced specimens after cooling.

5. Conclusions

The following conclusions can be drawn on the basis of the test results briefly described in this paper:

- The formation of heat-induced longitudinal splitting cracks, and eventual failure of the concrete cover's capacity to provide sufficient confining action, is more likely for FRP reinforced or prestressed concrete elements than for those reinforced or prestressed with steel during fire. This is due at least partly to the thermomechanical incompatibility (i.e. differential thermal expansion) between FRP reinforcement and concrete. Many aspects of bond performance at elevated temperature remain poorly understood and require additional investigation for FRP reinforced or prestressed elements which are bond critical.
- As the test specimens in this study were cast with unreinforced reinforcements (CFRP or steel) and tested under a free-to-expand, unrestrained condition, the effects of thermomechanical incompatibility have been evaluated in isolation from other mechanical actions encountered in large scale testing of real structural elements (e.g. bursting stresses in the prestress transfer zone). Additional testing is required to better understand these and other complexities.
- The H-TRIS testing methodology is able to accurately quantify the thermal conditions encountered in a large scale fire resistance test, with high precision and repeatability, and at negligible economical and temporal cost.
- The limitations of available analytical models currently used to describe the appearance of heat-induced longitudinal splitting cracks in FRP reinforced concrete elements are mainly driven by the assumption of a uniform temperature increase within the concrete specimen. Modelling work is currently underway to overcome this simplification.

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7. References

ABDALLA H, "Concrete cover requirements for FRP reinforced members in hot climates", *Composite Structures*, Vol. 73, No. 1, May 2006, pp. 61-69.

ACI, "Guide for the design and construction of concrete reinforced with FRP bars (ACI 440.1R-06)", *American Concrete Institute*, US, 2006, 44pp.

AIELLO MA, FOCACCI F, and NANNI A, "Effects of thermal load son concrete cover of fiber-reinforced polymer reinforced elements: theoretical and experimental analysis", *ACI Materials Journal*, Vol. 98, No. 4, July 2001, pp. 332-339.

BAFALAS I and BURGOYNE CJ, "Economic design of beams with FRP rebar or prestress", *Magazine of Concrete Research*, Vol. 64, No. 10, October 2012, pp. 885-898.

BISBY LA, GREEN MF, and KODUR VKR, "Response to fire of concrete structures that incorporate FRP", *New Materials in Construction*, Vol. 7, No. 3, April 2005, pp. 136-149.

CEN, "Design of concrete structures, Part 1.2: General rules – Structural fire design (EN 1992-1-2)", *European Committee for Standardization*, 2004, 100pp.

CNR, "Guide for the design and construction of concrete structures reinforced with fiber-reinforced polymer bars (CNR-DT 203/2006)", *National Research Council*, Italy, 2006, 35pp.

HARMATHY TZ and LIE TT, "Fire Test Standard in the Light of Fire Research", *Fire Test Performance – American Society for Testing and Materials (ASTM STP 464)*, 1970, pp. 85-97.

KATZ A, BERMAN N, and BANK LC, "Effect of high temperature on bond strength of FRP rebars", *Journal of Composites for Construction*, Vol. 3, No. 2, May 1999, pp. 73-81.

KATZ A and BERMAN N, "Modeling the effect of high temperature on the bond of FRP reinforcing bars to concrete", *Cement and Concrete Composites*, Vol. 22, No. 6, December 2000, pp. 433-443.

MALUK C, BISBY L, SANTA MARIA H, TERRASI G, and GREEN M, "Effects of Elevated Temperatures and Fire on Bond Strength of Prestressed Steel and Carbon FRP Bars in High Performance Self-Consolidating Concrete", *Proceedings of the 2nd Postgraduate Engineering Students' PUC Congress*, May 2010, 11pp.

MALUK C, BISBY L, TERRASI G, and GREEN M. "Bond strength degradation for CFRP and steel reinforcing bars in concrete at elevated temperature", *Innovations in fire design of concrete structures (ACI SP 279), American Concrete Institute*, 2011, 36pp.

MALUK C, BISBY L, TERRASI G, KRAJCOVIC M, and TORERO JL, "Novel Fire Testing Methodology: Why, How and What Now?", *Proceedings of the 1st International Conference on Performance Based and Life Cycle Structural Engineering (PLSE)*, December 2012, 11pp.

MALUK C, BISBY L, and TERRASI G. "Effects of polypropylene fibre type on occurrence of heat-induced concrete spalling", *Proceedings of the 3rd International Workshop Concrete Spalling due to Fire Exposure*, September 2013, 8pp.

TERRASI G, BISBY L, BARZBEZAT M, AFFOLTER C, and HUGI E. "Fire Behavior of Thin CFRP Pretensioned High-Strength Concrete Slabs, *Journal of Composites for Construction*, Vol. 16, No. 4, August 2012, pp. 381-394.